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Efficient Cooperative Spectrum Sensing for Three-Hop Cognitive Wireless Relay Networks

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Abstract

This paper is concerned with cooperative spectrum sensing (CSS) mechanisms in three-hop cognitive wireless relay networks (CWRNs). The data transmission from a source to a destination is realised with the aid of two layers of cognitive radio (CR) users which are in the transmission coverage of two primary users. In this paper, we first propose a new CSS scheme for a layer of CR users to improve the spectrum sensing performance by exploiting both local decisions at the CR users and global decisions at the fusion centre. Particularly, we derive the probabilities of missed detection and false alarm for a practical scenario where all sensing, reporting, and backward channels suffer from Rayleigh fading. The derived expressions not only show that our proposed CSS achieves a better sensing performance than the conventional scheme but also characterise the effects of the fading channels on the sensing reliability. Furthermore, we propose a CSS scheme for two CR layers in a three-hop CWRN using binary XOR operator to help reduce one phase of sensing for a higher system throughput.

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I. Introduction

Recently, cooperative communications has attracted growing interest in wireless communications with various enhanced technologies to improve data throughput and transmission quality by exploiting spatial diversity gains [1], [2]. To cope with the scarcity of spectrum resources, cognitive radio (CR) was proposed as an emerging technology to improve spectrum efficiency by providing dynamic spectrum access [3], [4]. In order to detect the occupation and reappearance of a primary user (PU), CR users must continuously monitor the spectrum, and thus spectrum sensing is one of the most basic elements in CR technology. Various well-known signal detection methods have been applied to spectrum sensing technology [5]. However, the implementation of these spectrum sensing techniques is not feasible for hidden terminal problems when the CR users suffer from shadowing or severe fading effects while their nearby PUs are active.

Motivated by relaying techniques for cooperative communications, cooperative spectrum sensing (CSS) was proposed not only to help the shadowed CR users detect the PUs but also to improve detection reliability by carrying out spectrum sensing in a cooperative manner [6], [7]. A CSS scheme can be divided into three phases, namely the sensing (SS) phase, reporting (RP) phase, and backward (BW) phase. These phases can be summarised as follows: Initially, every CR user carries out local spectrum sensing (LSS) in the SS phase to determine locally the existence of the PU. Then, all CR users forward their decisions to a fusion centre (FC), i.e., a common receiver, in the RP phase. Based on the local decisions received from various CR users, the FC makes a global decision on the existence of the PU and then broadcasts this decision to all CR users in the BW phase. Over the wireless medium, the CSS scheme suffers interference and noise from all the SS, RP, and BW channels. However, most published work assumes that the RP channels are error-free [8], [9] and that the BW channels are also error-free [7]. Additionally, in practical applications, e.g., in wireless ad hoc or sensor networks, the relay-aided data transmission from the source to the destination node can be realised via various transmission paths or hops. This stimulates us to consider a three-hop wireless relay network as a specific model of multi-hop communications[1]. In this model, two layers of relay nodes help the source transmit data to the destination.

[1] The considered model is extendible to a general relay network with more than three hops by changing the operations performed at the fusion centre to adapt to various network configurations.

In this paper, we investigate the spectrum sensing in a three-hop cognitive wireless relay network (CWRN) where a source node $\mathcal{S}$ transmits data to a destination node $\mathcal{D}$ via two layers of relay nodes. In a CR environment, the relay nodes can be regarded as CR users and two layers of relay nodes can be accordingly referred to as two layer of CR users. Each layer of CR users is assumed to be within the coverage of a CR network corresponding to the transmission range of a PU [10]. Inspired by cooperative spectrum sharing, the CWRN can generate a seamless transmission from $\mathcal{S}$ to $\mathcal{D}$ by exploiting some portions of the spectrum that may not be utilized by the PUs over a period of time. Specifically, cooperative diversity was incorporated into cognitive networks to realise cooperative spectrum sharing [10]–[13]. In [10], the authors proposed a cognitive space-time-frequency coding to maximize the spectrum opportunities in the CWRN. In [11], the CR users perform the role of a relay to assist the data transmission of the PU to increase their opportunities in spectrum access. In [12], a cooperative diversity scheme was proposed for CWRN where the CR users cooperatively send both the signal of the PU and their own signals. In [13], a cooperative scheme was proposed to improve the secondary outage probability by optimally selecting the best CR user as the relay for the secondary data transmission. However, the cooperative spectrum sharing in the three-hop CWRN poses the question of *how the CR users in two layers can efficiently sense the spectrum holes of both PUs to exploit all the available frequency bands in both CR networks for cooperative communications*.

Dealing with the spectrum sensing in three-hop CWRNs, we first consider the CSS for a layer of CR users and then extend to the whole system consisting of two layers of CR users. Specifically, for a CR layer, we propose a new CSS scheme to improve the spectrum sensing performance by exploiting both the local and global decisions in spectrum sensing at each CR user. The basic idea of our proposed scheme for a CR layer is that each CR user combines its local decision in the SS phase with the global decision of the FC in the BW phase. Also, we take into account a practical scenario where all the SS, RP, and BW channels are characterised by Rayleigh flat fading channels. To the best of our knowledge, this has received less interest. By deriving the expression of the probability of missed detection and false alarm, we not only show that our proposed CSS scheme achieves a better CSS performance than the conventional

CSS scheme[2] but also evaluate the effects of all the SS, RP, and BW channels on the CSS performance.

Extending to the whole system consisting of two layers of CR users in a three-hop CWRN, a total of eight phases is conventionally required to sense the available spectrum of both PUs at each CR user, including six phases for the CSS of two CR layers and two phases at the FC for the exchange of spectrum information between two CR layers. As the second contribution of the paper, we propose a new CSS scheme for three-hop CWRNs using binary XOR operator. With our proposed XOR-based CSS scheme, the number of phases is reduced by one, and thus the system throughput is improved. The basic idea of our proposed scheme is that the FC combines two decisions of the available spectrum of two PUs and then broadcasts this combination to all the CR users in two layers. Based on the known spectrum information at a CR user, the spectrum information of the PU in another layer can be extracted. It can be seen that the signalling number for the spectrum information is reduced by half with a simple XOR operator in our proposed scheme when compared with the conventional scheme[3]. Thus, the system throughput is considerably improved, especially when the number of frequency bands in the wide-band channel is large. This accordingly confirms that our proposed simple XOR operator in the CSS scheme is efficient.

II. System Model and Local Spectrum Sensing

A. System Model

Fig. 1 illustrates the system model of the three-hop cognitive wireless relay network under investigation. The data transmission from source node $\mathcal{S}$ to destination node $\mathcal{D}$ is accomplished via three hops with the assistance of two layers of relay nodes which are referred to as CR users. The routing tables for the data transmission are established at runtime based on the sensing results at the CR users. We assume that there are two PUs, namely $\mathcal{PU}_1$ and $\mathcal{PU}_2$, in the network and each CR user is within the transmission range of one PU. For convenience, let N_1 and N_2 denote the number of CR users in the first and second layer, respectively. Accordingly, we can

[2]The conventional CSS scheme for a CR layer is defined as the scheme where there is no combination of the local and global decision at the CR users in the BW phase.

[3]The conventional CSS scheme for two CR layers is defined as the process of eight phases, including six phases for the CSS of two layers and two phases at the FC for the exchange of spectrum information between two layers.

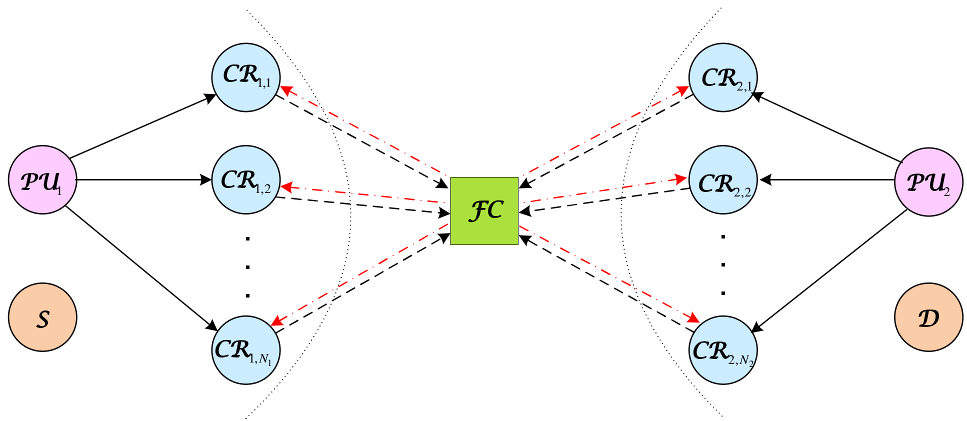

Fig. 1. Sensing process in cognitive wireless relay network.

represent the CR users in two layers as $\mathcal{CR}^{(N_1)} = \{\mathcal{CR}_{1,1},\, \mathcal{CR}_{1,2},\, \ldots, \mathcal{CR}_{1,N_1}\}$ and $\mathcal{CR}^{(N_2)} = \{\mathcal{CR}_{2,1},\, \mathcal{CR}_{2,2},\, \ldots, \mathcal{CR}_{2,N_2}\}$. Here, $\mathcal{CR}^{(N_1)}$ are referred to as relay candidates at the first relay hop $\mathcal{S} \to \mathcal{CR}^{(N_1)}$ and potential senders at the second relay hop $\mathcal{CR}^{(N_1)} \to \mathcal{CR}^{(N_2)}$, while $\mathcal{CR}^{(N_2)}$ are considered as relay candidates at the third relay hop $\mathcal{CR}^{(N_2)} \to \mathcal{D}$. The two PUs are assumed to operate in a wide-band channel including K non-overlapping frequency bands $f_1, f_2, \ldots, f_K$. A spectrum indicator vector (SIV) of length K (in bits) is used to report the availability of frequency bands in the transmission range of each PU where bits '0' and '1' represent the frequency band being utilized or available, respectively. The CSS of two CR layers is carried out over a common FC in a centralised manner (see Fig. 1). The FC is assumed to be located between the first and the second layer of the CR users and its role is to assist the spectrum sensing of all the CR users in both layers. We assume that the channels for all links are Rayleigh flat fading. The channel gains for the SS links $\mathcal{PU}_i \to \mathcal{CR}_{i,j}$, the RP links $\mathcal{CR}_{i,j} \to \mathcal{FC}$, and the BW links $\mathcal{FC} \to \mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, are denoted by $h_{P_iC_{i,j}}$, $h_{C_{i,j}F}$, and $h_{FC_{i,j}}$, respectively. All the channels are assumed to be time-invariant over the whole transmission of both the data and the SIV, and assumed to be known to all the nodes in the network.

B. Local Spectrum Sensing

Over the SS channel, the received signal at $\mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, can be expressed as

$$\mathbf{r}_{i,j}^{(SS)} = \begin{cases} h_{P_iC_{i,j}}\mathbf{x}_i + \mathbf{n}_{i,j}^{(SS)}, & \mathcal{H}_1^{(\mathcal{PU}_i)}, \\ \mathbf{n}_{i,j}^{(SS)}, & \mathcal{H}_0^{(\mathcal{PU}_i)}. \end{cases} \tag{1}$$

where $\mathbf{x}_i$ is the transmitted signal from $\mathcal{PU}_i$ and $\mathbf{n}_{i,j}^{(SS)}$ is the independent circularly symmetric complex Gaussian (CSCG) noise vector at $\mathcal{CR}_{i,j}$ over the SS channel. Here, $\mathcal{H}_1^{(\mathcal{PU}_i)} = \{\mathcal{H}_{1,1}^{(\mathcal{PU}_i)}, \mathcal{H}_{1,2}^{(\mathcal{PU}_i)}, \ldots, \mathcal{H}_{1,K}^{(\mathcal{PU}_i)}\}$ and $\mathcal{H}_0^{(\mathcal{PU}_i)} = \{\mathcal{H}_{0,1}^{(\mathcal{PU}_i)}, \mathcal{H}_{0,2}^{(\mathcal{PU}_i)}, \ldots, \mathcal{H}_{0,K}^{(\mathcal{PU}_i)}\}$ denote the hypothesis that the frequency bands are occupied by $\mathcal{PU}_i$ and the hypothesis that the frequency bands are available for CR users, respectively. We notice that the vectors in (1) have length K which corresponds to the number of frequency bands in the wide-band channel.

Then, following an energy detection rule for unknown signals over fading channels [14], $\mathcal{CR}_{i,j}$ can detect the usage of a k-th frequency band, $k = 1, 2, \ldots, K$, at $\mathcal{PU}_i$ by comparing the energy of the received signal $\mathbf{r}_{i,j}^{(SS)}[k]$ at the k-th frequency band with a corresponding energy threshold $\mathcal{E}_{i,j}[k]$, i.e.,

$$E\left[\mathbf{r}_{i,j}^{(SS)}[k]\right] \gtrless_{\mathcal{H}_{0,k}^{(\mathcal{CR}_{i,j})}}^{\mathcal{H}_{1,k}^{(\mathcal{CR}_{i,j})}} \mathcal{E}_{i,j}[k], \tag{2}$$

where $E[.]$ represents the energy measurement of a signal. Here, $\mathcal{H}_{1,k}^{(\mathcal{CR}_{i,j})}$ and $\mathcal{H}_{0,k}^{(\mathcal{CR}_{i,j})}$ denote the estimated hypotheses at $\mathcal{CR}_{i,j}$ that the k-th frequency band is occupied and unoccupied, respectively, by $\mathcal{PU}_i$. Let $\mathbf{s}_{i,j}^{(SS)}$ denote the local SIV estimated at $\mathcal{CR}_{i,j}$ over the SS channel $h_{P_iC_{i,j}}$. We can mathematically formulate the k-th element, $k = 1, 2, \ldots, K$, of $\mathbf{s}_{i,j}^{(SS)}$ as

$$\mathbf{s}_{i,j}^{(SS)}[k] = \begin{cases} 0, & \text{if } E\left[\mathbf{r}_{i,j}^{(SS)}[k]\right] \geqslant \mathcal{E}_{i,j}[k], \text{ i.e., } \mathcal{H}_{1,k}^{(\mathcal{CR}_{i,j})}, \\ 1, & \text{otherwise, i.e., } \mathcal{H}_{0,k}^{(\mathcal{CR}_{i,j})}. \end{cases} \tag{3}$$

III. Proposed Cooperative Spectrum Sensing

A. Proposed CSS Scheme for A CR Layer

For simplicity, we investigate the CSS scheme performed at only one layer of CR users, e.g., $\mathcal{CR}^{(N_1)}$. The CSS scheme for the remaining CR layer, $\mathcal{CR}^{(N_2)}$, can be similarly obtained[4]. The proposed CSS scheme consists of three phases, which can be described as follows:

[4]Note that the CSSs for two layers of CR users can be carried out simultaneously.

1) Sensing Phase: In SS phase, each CR user carries out the LSS over SS channel. Specifically, $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, locally senses the available frequency bands of $\mathcal{PU}_1$ over the SS channel $h_{P_1 C_{1,j}}$, and then makes a binary decision in terms of an SIV denoted by $\mathbf{s}_{1,j}^{(SS)}$ (see (3)).

2) Reporting Phase: In the CSS scheme, the spectrum sensing at the CR users is carried out in a cooperative manner with the help of an FC. Over the RP channels, each CR user $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, forwards the local estimated SIV, i.e., $\mathbf{s}_{1,j}^{(SS)}$, to $\mathcal{FC}$. The received signals at $\mathcal{FC}$ from $\mathcal{CR}_{1,j}$ can be written by

$$\mathbf{r}_{1,j}^{(RP)} = \sqrt{\Lambda_{1,j}} h_{C_{1,j}F} \mathbf{x}_{1,j}^{(SS)} + \mathbf{n}_{1,j}^{(RP)}, \tag{4}$$

where $\Lambda_{1,j}$ is the transmission power of $\mathcal{CR}_{1,j}$, $\mathbf{x}_{1,j}^{(SS)}$ is the binary phase shift keying (BPSK) modulated version of $\mathbf{s}_{1,j}^{(SS)}$, and $\mathbf{n}_{1,j}^{(RP)}$ is the independent CSCG noise vector at $\mathcal{FC}$ over the RP channel with each entry having zero mean and variance of N_0.

Then, $\mathcal{FC}$ processes to decode the received signals from each $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$. Let us denote the decoded SIV at $\mathcal{FC}$ from $\mathcal{CR}_{1,j}$ over the RP channel as $\mathbf{s}_{1,j}^{(RP)}$. Combining all the decoded SIVs $\{\mathbf{s}_{1,j}^{(RP)}\}$ from all the CR users $\{\mathcal{CR}_{1,j}\}$, $\mathcal{FC}$ makes a global decision using the following OR rule:

$$\mathbf{s}_{FC_1}[k] = \begin{cases} 0, & \text{if } \sum_{j=1}^{N_1} \mathbf{s}_{1,j}^{(RP)}[k] < N_1, \text{ i.e., } \mathcal{H}_{1,k}^{(\mathcal{FC}_1)}, \\ 1, & \text{otherwise, i.e., } \mathcal{H}_{0,k}^{(\mathcal{FC}_1)}, \end{cases} \tag{5}$$

where $\mathbf{s}_{FC_1}$ of length K denote the global SIV estimated at $\mathcal{FC}$ for the first CR layer, $k = 1, 2, \ldots, K$, and, $\mathcal{H}_{1,k}^{(\mathcal{FC}_1)}$ and $\mathcal{H}_{0,k}^{(\mathcal{FC}_1)}$ denote the estimated hypotheses at $\mathcal{FC}$ of the k-th frequency band occupied and unoccupied, respectively, by $\mathcal{PU}_1$. Note that, in (5), the decision of the availability of the frequency bands at $\mathcal{FC}$ follows the principle of the OR rule, i.e., $\mathcal{FC}$ decides the k-th frequency band being utilized by $\mathcal{PU}_1$ (i.e., $\mathcal{H}_{1,k}^{(\mathcal{FC}_1)}$) when at least one SIV (i.e., $\mathbf{s}_{1,j}^{(RP)}$) out of N_1 SIVs indicates the k-th frequency band being unavailable (i.e., $\mathcal{H}_{1,k}^{(\mathcal{CR}_{1,j})}$ or $\mathbf{s}_{1,j}^{(RP)}[k] = 0$), and otherwise, $\mathcal{FC}$ decides the k-th frequency band being available.

3) Backward Phase: In the BW phase, the FC broadcasts the global SIV to all CR users over BW channels. The received signal at $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, can be written by

$$\mathbf{r}_{1,j}^{(BW)} = \sqrt{\Lambda_{FC}} h_{FC_{1,j}} \mathbf{x}_{FC_1} + \mathbf{n}_{1,j}^{(BW)}, \tag{6}$$

where Λ_{FC} is the transmission power of $\mathcal{FC}$, $\mathbf{x}_{FC_1}$ is the BPSK modulated version of $\mathbf{s}_{FC_1}$, and $\mathbf{n}_{1,j}^{(BW)}$ is the independent CSCG noise vector at $\mathcal{CR}_{1,j}$ over the BW channel with each entry having zero mean and variance of N_0. Then, $\mathcal{CR}_{1,j}$ decodes the received signal from $\mathcal{FC}$ as $\mathbf{s}_{1,j}^{(BW)}$.

In our proposed CSS scheme, each CR user combines its local SIV determined in the SS phase (i.e., $\mathbf{s}_{1,j}^{(SS)}$) with the global SIV received from the FC in the BW phase (i.e., $\mathbf{s}_{1,j}^{(BW)}$) using the OR rule as follows:

$$\mathbf{s}_{CR_{1,j}}[k] = \begin{cases} 0, & \text{if } \left(\mathbf{s}_{1,j}^{(SS)}[k] + \mathbf{s}_{1,j}^{(BW)}[k]\right) < 2, \text{ i.e., } \bar{\mathcal{H}}_{1,k}^{(\mathcal{CR}_{1,j})}, \\ 1, & \text{otherwise, i.e., } \bar{\mathcal{H}}_{0,k}^{(\mathcal{CR}_{1,j})}, \end{cases} \tag{7}$$

where $\mathbf{s}_{CR_{1,j}}$ denotes the final SIV at $\mathcal{CR}_{1,j}$, $k = 1, 2, \ldots, K$, and, $\bar{\mathcal{H}}_{1,k}^{(\mathcal{CR}_{1,j})}$ and $\bar{\mathcal{H}}_{0,k}^{(\mathcal{CR}_{1,j})}$ denote the globally estimated hypotheses at $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, of the k-th frequency band occupied and unoccupied, respectively, by $\mathcal{PU}_1$ considering both the local and global SIVs.

Remark 1 (*Higher Reliability in Spectrum Sensing*)**.** The proposed CSS scheme can determine the availability of frequency bands more reliably than the conventional scheme. In the conventional CSS scheme, the global SIV received at the CR users from the FC is also the final SIV. This means that the decision at the CR users using the conventional scheme depends totally on the decision at the FC. Instead, in our proposed scheme, the final SIV at the CR users is the combination of two SIVs obtained from the LSS at the CR users and the CSS at the FC. As shown in (7), the hypothesis $\bar{\mathcal{H}}_{0,k}^{(\mathcal{CR}_{1,j})}$ is decided by $\mathbf{s}_{CR_{1,j}}[k] = 1$ if $\mathbf{s}_{1,j}^{(SS)}[k] = 1$ and $\mathbf{s}_{1,j}^{(BW)}[k] = 1$, which correspond to the hypotheses $\mathcal{H}_{0,k}^{(\mathcal{CR}_{1,j})}$ and $\mathcal{H}_{0,k}^{(\mathcal{FC}_1)}$. It can be seen that the frequency bands are finally determined to be available at the CR users only if both the LSS and CSS indicate that $\mathcal{PU}_1$ does not occupy these frequency bands. Therefore, the probability of missed detection is reduced.

B. Proposed XOR-based CSS scheme for Two CR Layers in Three-Hop CWRN

In this subsection, let us investigate a three-hop CWRN consisting of a source node $\mathcal{S}$, a destination node $\mathcal{D}$, and two layers of CR users $\mathcal{CR}^{(N_1)}$ and $\mathcal{CR}^{(N_2)}$, which are in the transmission range of $\mathcal{PU}_1$ and $\mathcal{PU}_2$, respectively (see Fig. 1). In order to realise a continuous transmission from $\mathcal{S}$ to $\mathcal{D}$ with the assistance of $\mathcal{CR}^{(N_1)}$ and $\mathcal{CR}^{(N_2)}$ in the three-hop CWRN, the spectrum can be shared in a cooperative manner to efficiently exploit the frequency bands that are not occupied by $\mathcal{PU}_1$ and $\mathcal{PU}_2$. Thus, all the CR users in two layers are required to sense the spectrum holes of both PUs.

The CSS scheme for each CR layer, as previously presented, consists of three phases to detect the available spectrum in the coverage of the corresponding PU. In order to help two CR layers know the spectrum information of each other, the conventional scheme requires two additional phases at $\mathcal{FC}$ to forward the global SIV of a CR layer to another layer, i.e., $\mathcal{FC}$ sequentially forwards $\mathbf{s}_{FC_1}$ and $\mathbf{s}_{FC_2}$ to $\mathcal{CR}^{(N_2)}$ and $\mathcal{CR}^{(N_1)}$, respectively. Accordingly, this results in a total of eight phases in the conventional CSS scheme for two layers of CR users in the three-hop CWRN. Exploiting XOR operator, we propose an XOR-based CSS scheme for two CR layers to reduce the exchanging time of the SIVs between $\mathcal{CR}^{(N_1)}$ and $\mathcal{CR}^{(N_2)}$. The proposed CSS scheme for two CR layers consists of seven phases as follows: SS, RP, and BW phases for $\mathcal{CR}^{(N_1)}$; SS, RP, and BW phases for $\mathcal{CR}^{(N_2)}$; and an exchange (EX) phase between $\mathcal{CR}^{(N_1)}$ and $\mathcal{CR}^{(N_2)}$.

Following the proposed CSS scheme for each layer of CR users in the first six phases, the final SIV at $\mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, and the global SIV at $\mathcal{FC}$ for the i-th CR layer are given by $\mathbf{s}_{CR_{i,j}}$ and $\mathbf{s}_{FC_i}$, respectively. In the EX phase of the proposed XOR-based CSS scheme, $\mathcal{FC}$ combines the global SIVs determined after two RP phases for two CR layers, i.e., $\mathbf{s}_{FC_1}$ and $\mathbf{s}_{FC_2}$, as

$$\mathbf{s}_{FC} = \mathbf{s}_{FC_1} \oplus \mathbf{s}_{FC_2}, \tag{8}$$

where $\oplus$ denotes the XOR operator and $\mathbf{s}_{FC}$ is the XOR-based combined SIV at $\mathcal{FC}$. Then, $\mathcal{FC}$ forwards $\mathbf{s}_{FC}$ to all CR users in two layers. The received signal at each CR user $\mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, can be written as

$$\mathbf{r}_{i,j}^{(EX)} = \sqrt{\Lambda_{FC}} h_{FC_{i,j}} \mathbf{x}_{FC} + \mathbf{n}_{i,j}^{(EX)}, \tag{9}$$

where $\mathbf{x}_{FC}$ is the BPSK modulated version of $\mathbf{s}_{FC}$, and $\mathbf{n}_{i,j}^{(EX)}$ is the independent CSCG noise vector at $\mathcal{CR}_{i,j}$ in the EX phase with each entry having zero mean and variance of N_0. Then, $\mathcal{CR}_{i,j}$ decodes the received signal as $\mathbf{s}_{i,j}^{(EX)}$. Note that the decoded signal at $\mathcal{CR}_{i,j}$ of the transmitted signal $\mathbf{s}_{FC_i}$ in the BW phase is given by $\mathbf{s}_{i,j}^{(BW)}$ (see (6)). Thus, $\mathcal{CR}_{i,j}$ in the i-th CR layer can detect the spectrum information of the $\bar{i}$-th CR layer, $\bar{i} = 1, 2$, $\bar{i} \neq i$, with XOR operator, i.e.,

$$\mathbf{s}_{CR_{i,j}}^{(\bar{i})} = \mathbf{s}_{i,j}^{(EX)} \oplus \mathbf{s}_{i,j}^{(BW)}, \tag{10}$$

where $\mathbf{s}_{CR_{i,j}}^{(\bar{i})}$ denotes the global SIV of the $\bar{i}$-th CR layer estimated at $\mathcal{CR}_{i,j}$.

Remark 2 (*Higher System Throughput with XOR Operator*)**.** The proposed XOR-based CSS scheme for two CR layers in the three-hop CWRN achieves a higher system throughput than the conventional CSS scheme. Let $T_{i,j}^{(SS)}$ and $T_{i,j}^{(RP)}$ denote the local sensing time and reporting time, respectively, for a frequency band at the j-th CR user in the i-th CR layer, $i = 1, 2$, $j = 1, 2, \ldots, N_i$. Also, let $T^{(BW)}$ and $T^{(EX)}$ denote the backward time and the exchange time, respectively, at FC for a frequency band. It can be seen that the conventional CSS scheme requires a total time of $\left[K\left(\sum_{i=1}^{2}\sum_{j=1}^{N_i} T_{i,j}^{(SS)} + T_{i,j}^{(RP)}\right) + 2KT^{(BW)} + 2KT^{(EX)}\right]$ whilst the total time in our proposed CSS scheme is $\left[K\left(\sum_{i=1}^{2}\sum_{j=1}^{N_i} T_{i,j}^{(SS)} + T_{i,j}^{(RP)}\right) + 2KT^{(BW)} + KT^{(EX)}\right]$. Thus, the proposed XOR-based CSS scheme reduces the time of spectrum sensing in the whole system by $KT^{(EX)}$, which accordingly results in a higher system throughput. It can also be observed that the combination operations performed at the CR user and the FC in the proposed scheme require a higher complexity processing. This may cause a delay of the spectrum sensing, and thus results in a lower system throughput or a decreased end-to-end relay performance of the data traffic. However, this delay is negligible when compared to the improved throughput achieved with our proposed CSS scheme.

IV. Performance Analysis of Cooperative Spectrum Sensing

In this section, we investigate two performance metrics for spectrum sensing in CWRNs including the missed detection probability (MDP)[5] and the false alarm probability (FAP)[6]. Specifically, we derive the expressions of MDP and FAP for the proposed CSS scheme over a practical scenario where all the SS, RP, and BW channels are characterised by Rayleigh flat fading channels. For convenience, let $P_m^{(A)}$ and $P_f^{(A)}$, $A \in \{\mathcal{CR}_{i,j}, \mathcal{FC}\}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, denote the MDP and FAP, respectively, at node A.

For the LSS at a CR user $\mathcal{CR}_{i,j}$, $i = 1, 2$, $j = 1, 2, \ldots, N_i$, the average FAP and MDP of the k-th frequency band over the SS channels are given by [14]

$$P_f^{(\mathcal{CR}_{i,j})} = \Pr\left\{\mathcal{H}_{1,k}^{(\mathcal{CR}_{i,j})} | \mathcal{H}_{0,k}^{(\mathcal{PU}_i)}\right\} = \Pr\left\{\mathbf{s}_{i,j}^{(SS)}[k] = 0 | \mathbf{x}_i = 0\right\} = \frac{\Gamma\left(\mu, \frac{\mathcal{E}_{i,j}[k]}{2}\right)}{\Gamma\left(\mu\right)}, \tag{11}$$

[5]MDP is defined as the probability that a CR user detects an available frequency band given that a PU currently occupies that frequency for transmission.

[6]FAP is defined as the probability that a CR user senses a frequency band occupied by a PU given that the PU does not operate on that frequency band.

$$P_m^{(\mathcal{CR}_{i,j})} = \Pr\left\{\mathcal{H}_{0,k}^{(\mathcal{CR}_{i,j})}|\mathcal{H}_{1,k}^{(\mathcal{PU}_i)}\right\} = \Pr\left\{\mathbf{s}_{i,j}^{(SS)}[k]=1|\mathbf{x}_i\neq 0\right\}$$

$$= 1 - e^{-\frac{\mathcal{E}_{i,j}[k]}{2}}\sum_{l=0}^{\mu-2}\frac{\mathcal{E}_{i,j}^l[k]}{l!2^l} - \left(\frac{1+\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})}}{\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})}}\right)^{\mu-1}\left[e^{-\frac{\mathcal{E}_{i,j}[k]}{2\left(1+\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})}\right)}} - e^{-\frac{\mathcal{E}_{i,j}[k]}{2}}\sum_{l=0}^{\mu-2}\frac{\mathcal{E}_{i,j}^l[k](\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})})^l}{l!2^l\left(1+\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})}\right)^l}\right], \tag{12}$$

respectively, where μ is the time-bandwidth product, $\gamma_{P_iC_{i,j}}^{(\mathcal{CR}_{i,j})}$ is average signal-to-noise ratio (SNR) at $\mathcal{CR}_{i,j}$ over the SS channel $h_{P_iC_{i,j}}$, and $\Gamma[a,b]$ is the upper incomplete gamma function defined as $\Gamma[a,b] \triangleq \int_b^\infty t^{a-1}e^{-t}dt$ [15].

Now, let us analyse the CSS scheme performed at only one layer of CR users, e.g., $\mathcal{CR}^{(N_1)}$. The analysis of the CSS scheme for the remaining CR layer, $\mathcal{CR}^{(N_2)}$, can be similarly obtained. In the CSS scheme, each CR user forwards the sensing information to FC over the RP channels. The FC then decodes all the received information and makes a global decision based on the OR rule. The FAP and MDP at the FC can be written as

$$P_f^{(\mathcal{FC}_1)} = \Pr\left\{\mathcal{H}_{1,k}^{(\mathcal{FC}_1)}|\mathcal{H}_{0,k}^{(\mathcal{PU}_1)}\right\} = \Pr\left\{\mathbf{s}_{FC_1}[k]=0|\mathbf{x}_1=0\right\}, \tag{13}$$

$$P_m^{(\mathcal{FC}_1)} = \Pr\left\{\mathcal{H}_{0,k}^{(\mathcal{FC}_1)}|\mathcal{H}_{1,k}^{(\mathcal{PU}_1)}\right\} = \Pr\left\{\mathbf{s}_{FC_1}[k]=1|\mathbf{x}_1\neq 0\right\}, \tag{14}$$

respectively. From (5), we can rewrite (13) and (14) as

$$P_f^{(\mathcal{FC}_1)} = 1 - \prod_{j=1}^{N_1}\Pr\left\{\mathbf{s}_{1,j}^{(RP)}[k]=1|\mathbf{x}_1=0\right\}, \tag{15}$$

$$P_m^{(\mathcal{FC}_1)} = \prod_{j=1}^{N_1}\Pr\left\{\mathbf{s}_{1,j}^{(RP)}[k]=1|\mathbf{x}_1\neq 0\right\}. \tag{16}$$

Thus, if considering an ideal case where the RP channels are error-free, i.e., $\mathbf{s}_{1,j}^{(RP)} = \mathbf{s}_{1,j}^{(SS)}$, from (11) and (12), the FAP and MDP at the FC can be written as

$$P_f^{(\mathcal{FC}_1,\text{error-free})} = 1 - \prod_{j=1}^{N_1}\left(1 - P_f^{(\mathcal{CR}_{1,j})}\right), \tag{17}$$

$$P_m^{(\mathcal{FC}_1,\text{error-free})} = \prod_{j=1}^{N_1}P_m^{(\mathcal{CR}_{1,j})}, \tag{18}$$

respectively. However, the RP channels suffer from fading and noise.

Over a Rayleigh flat fading channel h_{AB}, the bit error probability (BEP) for the transmission of BPSK modulated signal is given by [16]

$$P_b(E_{AB}) = \phi(\gamma), \tag{19}$$

where γ is the average SNR and $\phi(x) \triangleq \frac{1}{2}\left(1 - \sqrt{\frac{x}{1+x}}\right)$. Thus, taking into account the noisy RP channels $\left\{h_{C_{1,j}F}\right\}$, $j = 1, 2, \ldots, N_1$, the FAP and MDP at the FC are given by [7]

$$P_f^{(\mathcal{FC}_1)} = 1 - \prod_{j=1}^{N_1} \left[\left(1 - P_f^{(\mathcal{CR}_{1,j})}\right)\left(1 - P_b(E_{C_{1,j}F})\right) + P_f^{(\mathcal{CR}_{1,j})} P_b(E_{C_{1,j}F})\right], \tag{20}$$

$$P_m^{(\mathcal{FC}_1)} = \prod_{j=1}^{N_1} \left[P_m^{(\mathcal{CR}_{1,j})}\left(1 - P_b(E_{C_{1,j}F})\right) + \left(1 - P_m^{(\mathcal{CR}_{1,j})}\right) P_b(E_{C_{1,j}F})\right], \tag{21}$$

respectively. Here, $P_b(E_{C_{1,j}F}) = \phi(\gamma_{C_{1,j}F}^{(\mathcal{FC})})$ (see (19)), where $\gamma_{C_{1,j}F}^{(\mathcal{FC})}$ denotes the SNR at $\mathcal{FC}$ over the RP channel $h_{C_{1,j}F}$.

Then, in order to help each CR user decide the availability of the spectrum, the FC needs to forward its decision to all the CR users over the BW channels. In our proposed CSS scheme, $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, ORs its local SIV with the global SIV received from $\mathcal{FC}$ to make a final decision. Let $P_f^{'(\mathcal{CR}_{1,j})}$ and $P_m^{'(\mathcal{CR}_{1,j})}$ denote the FAP and MDP of the final decision at $\mathcal{CR}_{1,j}$ over the BW channels. We then have the following finding:

Lemma 1. FAP and MDP at $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, over the noisy BW channels $h_{FC_{1,j}}$ are determined by

$$\begin{aligned} P_f^{'(\mathcal{CR}_{1,j})} =& 1 - \left[\left(1 - P_f^{(\mathcal{CR}_{1,j})}\right)\left(1 - P_b(E_{FC_{1,j}})\right) + P_f^{(\mathcal{CR}_{1,j})} P_b(E_{FC_{1,j}})\right] \\ & \times \left[\left(1 - P_f^{(\mathcal{FC}_1)}\right)\left(1 - P_b(E_{FC_{1,j}})\right) + P_f^{(\mathcal{FC}_1)} P_b(E_{FC_{1,j}})\right], \end{aligned} \tag{22}$$

$$\begin{aligned} P_m^{'(\mathcal{CR}_{1,j})} =& \left[P_m^{(\mathcal{CR}_{1,j})}\left(1 - P_b(E_{FC_{1,j}})\right) + \left(1 - P_m^{(\mathcal{CR}_{1,j})}\right) P_b(E_{FC_{1,j}})\right] \\ & \times \left[P_m^{(\mathcal{FC}_1)}\left(1 - P_b(E_{FC_{1,j}})\right) + \left(1 - P_m^{(\mathcal{FC}_1)}\right) P_b(E_{FC_{1,j}})\right], \end{aligned} \tag{23}$$

respectively, where $P_b(E_{FC_{1,j}}) = \phi(\gamma_{FC_{1,j}}^{(\mathcal{CR}_{1,j})})$ and $\gamma_{FC_{1,j}}^{(\mathcal{CR}_{1,j})}$ denotes the SNR at $\mathcal{CR}_{1,j}$ over the BW channel $h_{FC_{1,j}}$.

Proof: See Appendix A. ■

Corollary 1. For identical SS and RP channels, i.e., $\gamma_{PC_{1,j}}^{(\mathcal{CR}_{1,j})} \triangleq \gamma_1^{(SS)}$ and $\gamma_{C_{1,j}F}^{(\mathcal{FC}_1)} \triangleq \gamma_1^{(RP)}$, $j = 1, 2, \ldots, N_1$, all CR users achieve the same FAP and MDP in the LSS process, i.e.,

$P_f^{(\mathcal{CR}_{1,j})} \triangleq P_f^{(\mathcal{CR}_1)}$ and $P_m^{(\mathcal{CR}_{1,j})} \triangleq P_m^{(\mathcal{CR}_1)}$, and, the BEPs of all the RP channels are identical, i.e., $P_b(E_{C_{1,j}F}) \triangleq P_b(E_{C_1F}) = \phi(\gamma_1^{(RP)})$. Then, the FAP at $\mathcal{CR}_{1,j}$ over the BW channels is lower-bounded by $P_{f,0}^{'(\mathcal{CR}_{1,j})}$, where

$$P_{f,0}^{'(\mathcal{CR}_{1,j})} = 1-(1-N_1P_b(E_{C_1F}))\left(1-P_b(E_{FC_{1,j}})\right)^2-N_1P_b(E_{C_1F})P_b(E_{FC_{1,j}})\left(1-P_b(E_{FC_{1,j}})\right). \tag{24}$$

Proof: See Appendix B. ■

Remark 3 (*Improved MDP and Higher Lower-Bound of FAP with Increased Number of CR Users*)**.** The proposed CSS scheme improves the MDP at the CR users and increases the lower bound of the FAP when the number of CR users increases. In fact, from (21), it can be seen that $P_m^{(\mathcal{FC}_1)}$ monotonically decreases over N_1. Thus, $P_m^{'(\mathcal{CR}_{1,j})}$, $j = 1, 2, \ldots, N_1$, given by (23) is a decreasing function over N_1. This means that the MDP at $\mathcal{CR}_{1,j}$ is improved as the number of CR users increases. In addition, from (24), it can be proved that $P_{f,0}^{'(\mathcal{CR}_{1,j})}$ monotonically increases over N_1. In other words, the increased number of CR users results in the higher lower bound of the FAP at $\mathcal{CR}_{1,j}$. This observation will be confirmed later in the numerical results where the FAP at $\mathcal{CR}_{1,j}$ is limited by the lower threshold and the MDP increases quickly to one as the FAP approaches this threshold.

Remark 4 (*Better Sensing Performance with Our Proposed CSS Scheme*)**.** The proposed CSS scheme at the CR users achieves a better performance than the conventional scheme in terms of MDP. In fact, following the conventional CSS scheme, the final SIV at the CR users is obtained from the global SIV at the FC, which means that $\mathrm{s}_{CR_{1,j}}$, $j = 1, 2, \ldots, N_1$, depends totally on s_{FC_1}. Thus, the MDP of the conventional CSS scheme at $\mathcal{CR}_{1,j}$ is given by

$$P_m^{'(\mathcal{CR}_{1,j},\text{conventional})} = P_m^{(\mathcal{FC}_1)}\left(1-P_b(E_{FC_{1,j}})\right) + \left(1-P_m^{(\mathcal{FC}_1)}\right)P_b(E_{FC_{1,j}})\forall j = 1, 2, \ldots, N_1, \tag{25}$$

where $P_m^{(\mathcal{FC}_1)}$ is given by (21). Let us denote G as the performance gain achieved with our proposed CSS scheme compared with the conventional scheme, which is defined as

$$G \triangleq \frac{P_m^{'(\mathcal{CR}_{1,j})}}{P_m^{'(\mathcal{CR}_{1,j},\text{conventional})}}. \tag{26}$$

From (23) and (25), we obtain

$$G = P_m^{(\mathcal{CR}_{1,j})}\left(1-P_b(E_{FC_{1,j}})\right) + \left(1-P_m^{(\mathcal{CR}_{1,j})}\right)P_b(E_{FC_{1,j}}). \tag{27}$$

It can be seen that $G < 1$ for all $P_m^{(\mathcal{CR}_{1,j})}$, $P_m^{(\mathcal{FC}_1)}$, and $P_b(E_{FC_{1,j}})$. In other words, independent of the LSS at the CR users, the CSS at the FC, and the quality of the BW channels, our proposed CSS scheme achieves a lower MDP than the conventional scheme. Additionally, a significant gain is achieved with our proposed scheme (i.e., a much lower G) when either the BW channels is at high SNR (i.e., a very low $P_b(E_{FC_{1,j}})$) or the LSS at the CR users is very reliable (i.e., a very low $P_m^{(\mathcal{CR}_{1,j})}$).

V. Numerical Results

In this section, we present numerical results of the MDP and FAP using various spectrum sensing schemes. Specifically, the relationship between the MDP and the FAP is represented by the complementary receiver operating characteristic (CROC), which is defined as the MDP versus the FAP [14].

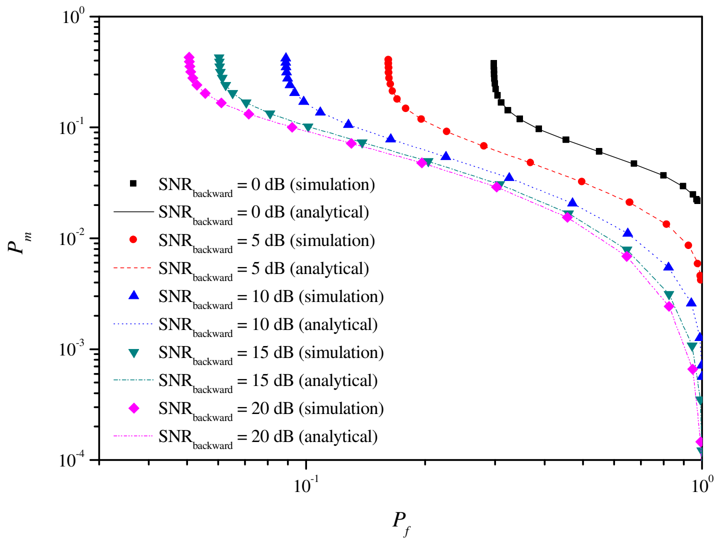

Fig. 2. Cooperative spectrum sensing performance at a CR user ($\mathcal{CR}_{1,1}$) over backward links with 2 CR users, $\gamma_{P_1C_{1,1}}^{(\mathcal{CR}_{1,1})} = \gamma_{P_1C_{1,2}}^{(\mathcal{CR}_{1,2})} = \gamma_{C_{1,1}F}^{(\mathcal{FC})} = \gamma_{C_{1,2}F}^{(\mathcal{FC})} = 10$ dB, and various $\gamma_{FC_{1,1}}^{(\mathcal{CR}_{1,1})}$.

In Fig. 2, the CSS performance at a CR user using our proposed scheme is illustrated with respect to various SNR values of the BW channel. We assume that there are 2 CR users in the first layer, i.e., $\mathcal{CR}_{1,1}$ and $\mathcal{CR}_{1,2}$ and the CROC curves are corresponding to the sensing performance at $\mathcal{CR}_{1,1}$. The SNRs of the SS and RP channels are assumed to be $\gamma_{C_{1,1}F}^{(\mathcal{FC})} = \gamma_{C_{1,2}F}^{(\mathcal{FC})} = \gamma_{P_1C_{1,1}}^{(\mathcal{CR}_{1,1})} = \gamma_{P_1C_{1,2}}^{(\mathcal{CR}_{1,2})} = 10$ dB and the SNR of the BW channel, i.e., $\gamma_{FC_{1,1}}^{(\mathcal{CR}_{1,1})}$, is assumed to vary in

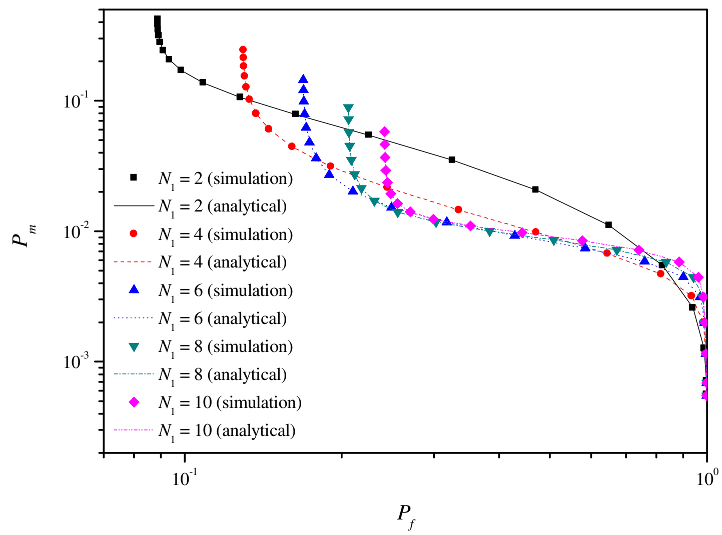

Fig. 3. Cooperative spectrum sensing performance at a CR user ($\mathcal{CR}_{1,1}$) over backward links with $\gamma_{P_1C_{1,j}}^{(\mathcal{CR}_{1,j})} = \gamma_{C_{1,j}F}^{(\mathcal{FC})} = \gamma_{FC_{1,j}}^{(\mathcal{CR}_{1,j})} = 10$ dB, $j = 1, 2, \ldots, N_1$, and various number of CR users (N_1).

$\{0, 5, 10, 15, 20\}$ dB. It can be seen that the sensing performance at $\mathcal{CR}_{1,1}$ is significantly reduced when $\gamma_{FC_{1,1}}^{(\mathcal{CR}_{1,1})}$ decreases. This observation reflects the effects of the BW channels on the CSS performance. Additionally, the analytical results are shown to be matched with the simulation results. In order to investigate the effects of number of CR users on the CSS performance, Fig. 3 illustrates the CROC curves of the CSS at $\mathcal{CR}_{1,1}$ with respect to various number of CR users. The SNRs of the SS, RP, and BW channels are assumed to be 10 dB and the number of CR users (i.e., N_1) is assumed to be in $\{2, 4, 6, 8, 10\}$. We observe that the MDP is lower and the lower-bound of FAP is higher when N_1 increases. This observation confirms the statements in Remark 3 regarding the improved MDP and higher lower-bound of FAP with the increased number of CR users in our proposed scheme.

For the comparison between our proposed CSS scheme and the conventional scheme, Fig. 4 shows the CROC of both CSS schemes with respect to various SNR values of the BW channel. The CROC curves are plotted for the CSS at $\mathcal{CR}_{1,1}$ in the first CR layer including 2 CR users $\mathcal{CR}_{1,1}$ and $\mathcal{CR}_{1,2}$. The SNRs of the SS, RP, and BW channels are assumed as follows: $\gamma_{C_{1,1}F}^{(\mathcal{FC})} = \gamma_{C_{1,2}F}^{(\mathcal{FC})} = \gamma_{P_1C_{1,1}}^{(\mathcal{CR}_{1,1})} = \gamma_{P_1C_{1,2}}^{(\mathcal{CR}_{1,2})} = 10$ dB and $\gamma_{FC_{1,1}}^{(\mathcal{CR}_{1,1})} \in \{0, 10, 20\}$ dB. It can be seen that our proposed CSS scheme achieves better sensing performance than the conventional scheme for all SNR values of the BW channels. This observation confirms the statements in Remarks 1 and

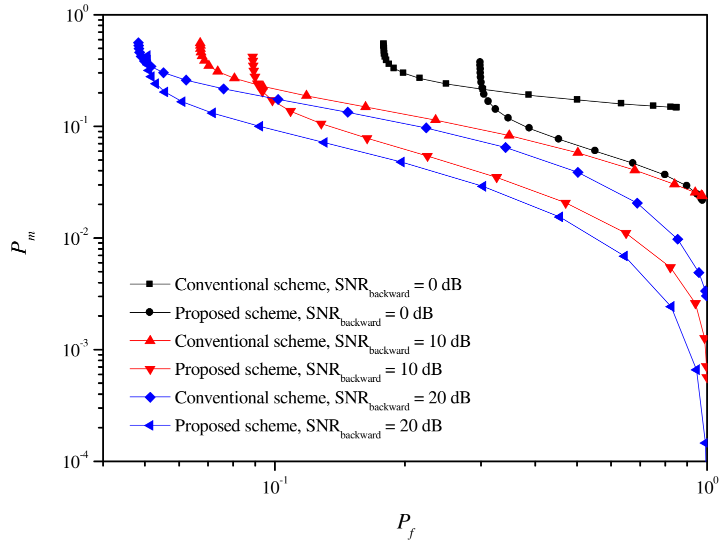

Fig. 4. Comparison of two cooperative spectrum sensing schemes over backward links with 2 CR users, $\gamma_{P_1C_{1,1}}^{(\mathcal{CR}_{1,1})} = \gamma_{P_1C_{1,2}}^{(\mathcal{CR}_{1,2})} = \gamma_{C_{1,1}F}^{(\mathcal{FC})} = \gamma_{C_{1,2}F}^{(\mathcal{FC})} = 10$ dB, and various $\gamma_{FC_{1,1}}^{(\mathcal{CR}_{1,1})}$.

4 about the improved reliability of spectrum sensing with our proposed CSS scheme. In fact, in our proposed scheme, the combination of the LSS and CSS at the CR user results in better sensing performance at the CR users.

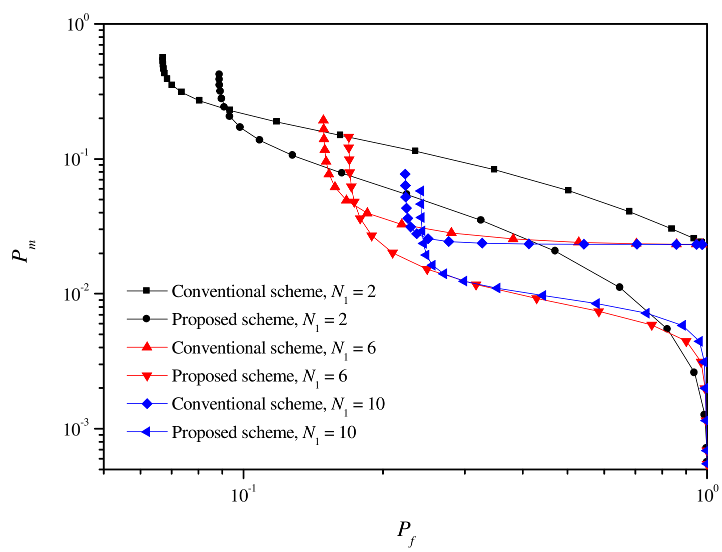

Fig. 5. Comparison of two cooperative spectrum sensing schemes over backward links with $\gamma_{P_1C_{1,j}}^{(\mathcal{CR}_{1,j})} = \gamma_{C_{1,j}F}^{(\mathcal{FC})} = \gamma_{FC_{1,j}}^{(\mathcal{CR}_{1,j})} = 10$ dB, $j = 1, 2, \ldots, N_1$, and various number of CR users (N_1).

Investigating the effects of the number of CR users on the sensing performance, Fig. 5 plots the CROC of both our proposed CSS scheme and the conventional scheme with respect to various number of CR users (i.e., N_1). We assume that the SNRs of the SS, RP, and BW channels are 10 dB, and, N_1 in $\{2, 6, 10\}$. Similarly, it can be observed that our proposed scheme achieves better performance than the conventional scheme for all values of N_1. This also confirms the statements in Remarks 1 and 4 about the improved sensing performance with our proposed CSS scheme.

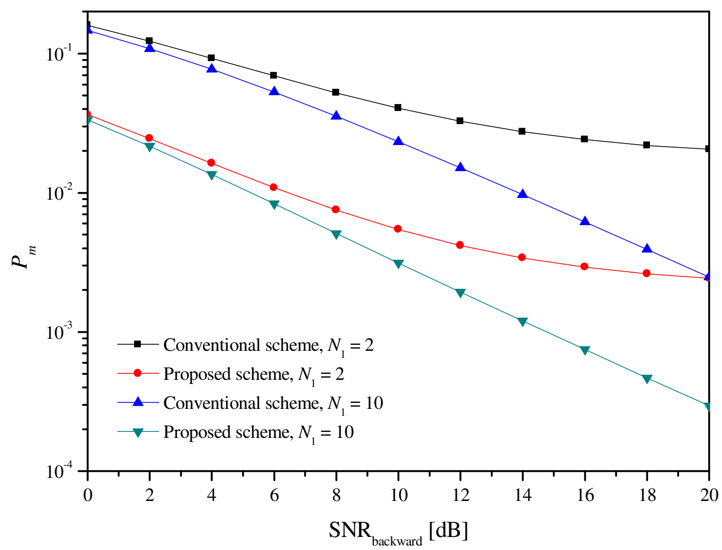

Fig. 6. MDP of cooperative spectrum sensing over SNR of backward links with $\gamma_{P_1 C_{1,j}}^{(\mathcal{CR}_{1,j})} = \gamma_{C_{1,j} F}^{(\mathcal{FC})} = 10$ dB, $j = 1, 2, \ldots, N_1$, and various N_1.

Taking into consideration the MDP, Figs. 6 and 7 plot the MDP of various CSS schemes versus SNR of the BW channels and versus number of CR users, respectively. In Fig. 6, the SNRs of the SS and RP channels are 10 dB, and, N_1 in $\{2, 10\}$. It can be seen that our proposed scheme achieves a much lower MDP than the conventional scheme. For example, 8 dB is improved with our proposed scheme for a MDP of 10^{-2} and $N_1 = 10$. The effectiveness of our proposed scheme is further confirmed in Fig. 7 where the MDP of both our proposed CSS scheme and the conventional scheme is plotted over the number of CR users. The SNRs of the SS and RP channels are 10 dB, while the SNRs of the BW channels are in $\{10, 20\}$ dB. We observe that the MDP of our proposed scheme is better than that of the conventional scheme for any value of either N_1 or SNR of BW links. Specifically, for a SNR of BW channels of 20 dB, our proposed

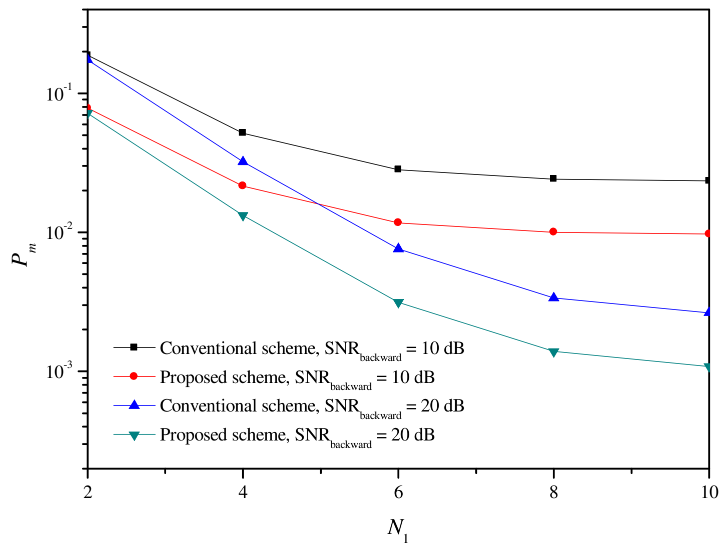

Fig. 7. MDP of cooperative spectrum sensing over N_1 with $\gamma_{P_1C_{1,j}}^{(\mathcal{CR}_{1,j})} = \gamma_{C_{1,j}F}^{(\mathcal{FC})} = 10$ dB, $j = 1, 2, \ldots, N_1$, and various SNRs of backward links.

scheme achieves the MDP of 10^{-2} with 4 CR users while 6 CR users are required to achieve the same MDP using the conventional scheme. The aforementioned observations from Figs. 6 and 7 confirm the statements in Remarks 1 and 4 regarding a better MDP with our proposed CSS scheme.

VI. Conclusions

In this paper, we have proposed two CSS schemes for three-hop CWRNs. Exploiting both the local decisions at the CR users and global decisions at the FC, a better sensing performance is achieved with our first proposed scheme. An analysis of the probabilities of missed detection and false alarm has been carried out with respect to the SNRs of SS, RP, and BW channels. The derived expressions reflect well the impacts of the quality of the SS, RP, and BW links upon the sensing performance and confirm the improvement of sensing reliability with our proposed scheme. Moreover, for the exchange of spectrum information between two CR layers, we have proposed an XOR-based CSS scheme to reduce the number of signallings for a higher system throughput. In addition, simulations have been provided which have confirmed the analytical results. For future work, we will investigate the CSS for CWRNs with more than three hops. Also, we will investigate the optimisation of the FC location for the best sensing performance.

APPENDIX A
PROOF OF LEMMA 1

The FAP and MDP at $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, can be computed by

$$P_f^{\prime(\mathcal{CR}_{1,j})} = \textbf{Pr}\left\{\bar{\mathcal{H}}_{1,k}^{(\mathcal{CR}_{1,j})}|\mathcal{H}_{0,k}^{(\mathcal{PU}_1)}\right\} = \textbf{Pr}\left\{\mathbf{s}_{CR_{1,j}}[k] = 0|\mathbf{x}_1 = 0\right\}, \tag{28}$$

$$P_m^{\prime(\mathcal{CR}_{1,j})} = \textbf{Pr}\left\{\bar{\mathcal{H}}_{0,k}^{(\mathcal{CR}_{1,j})}|\mathcal{H}_{1,k}^{(\mathcal{PU}_1)}\right\} = \textbf{Pr}\left\{\mathbf{s}_{CR_{1,j}}[k] = 1|\mathbf{x}_1 \neq 0\right\}. \tag{29}$$

From (7), we can rewrite (28) and (29) as

$$P_f^{\prime(\mathcal{CR}_{1,j})} = 1 - \textbf{Pr}\left\{\mathbf{s}_{1,j}^{(SS)}[k] = 1|\mathbf{x}_1 = 0\right\}\textbf{Pr}\left\{\mathbf{s}_{1,j}^{(BW)}[k] = 1|\mathbf{x}_1 = 0\right\}, \tag{30}$$

$$P_m^{\prime(\mathcal{CR}_{1,j})} = \textbf{Pr}\left\{\mathbf{s}_{1,j}^{(SS)}[k] = 1|\mathbf{x}_1 \neq 0\right\}\textbf{Pr}\left\{\mathbf{s}_{1,j}^{(BW)}[k] = 1|\mathbf{x}_1 \neq 0\right\}. \tag{31}$$

In the situation that there is no error in the BW phase, i.e., $\mathbf{s}_{1,j}^{(BW)} = \mathbf{s}_{FC_1}$, substituting (11), (12), (13), and (14) into (30) and (31), we obtain

$$P_f^{\prime(\mathcal{CR}_{1,j},\text{error-free})} = 1 - \left(1 - P_f^{(\mathcal{CR}_{1,j})}\right)\left(1 - P_f^{(\mathcal{FC}_1)}\right), \tag{32}$$

$$P_m^{\prime(\mathcal{CR}_{1,j},\text{error-free})} = P_m^{(\mathcal{CR}_{1,j})}P_m^{(\mathcal{FC}_1)}. \tag{33}$$

Therefore, over the noisy BW channels $h_{FC_{1,j}}$, we obtain the FAP and MDP at $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, as (22) and (23), respectively.

APPENDIX B
PROOF OF COROLLARY 1

From (22), the FAP at $\mathcal{CR}_{1,j}$, $j = 1, 2, \ldots, N_1$, over the BW channels can be rewritten as

$$\begin{aligned} P_f^{\prime(\mathcal{CR}_{1,j})} =& 1 - \left(1 - P_f^{(\mathcal{CR}_{1,j})}\right)\left(1 - P_f^{(\mathcal{FC}_1)}\right)\left(1 - P_b(E_{FC_{1,j}})\right)^2 \\ & - P_b(E_{FC_{1,j}})(1 - P_b(E_{FC_{1,j}}))\left[P_f^{(\mathcal{CR}_{1,j})} + P_f^{(\mathcal{FC}_1)} - 2P_f^{(\mathcal{CR}_{1,j})}P_f^{(\mathcal{FC}_1)}\right] \\ & - P_f^{(\mathcal{CR}_{1,j})}P_f^{(\mathcal{FC}_1)}(P_b(E_{FC_{1,j}}))^2. \end{aligned} \tag{34}$$

It can be seen that the FAP of the CSS scheme is lower-bounded if the FAP of the LSS scheme approaches to zero. Let us denote $P_{f,0}^{\prime(\mathcal{CR}_{1,j})}$ as the lower bound of $P_f^{\prime(\mathcal{CR}_{1,j})}$. Then

$$P_{f,0}^{\prime(\mathcal{CR}_{1,j})} = \lim_{P_f^{(\mathcal{CR}_1)} \to 0} P_f^{\prime(\mathcal{CR}_{1,j})}. \tag{35}$$

Since $P_f^{(\mathcal{CR}_{1,j})} = P_f^{(\mathcal{CR}_1)}$, $P_m^{(\mathcal{CR}_{1,j})} = P_m^{(\mathcal{CR}_1)}$, and $P_b(E_{C_{1,j}F}) = P_b(E_{C_1F})$, $\forall j = 1, 2, \ldots, N_1$, from (20), the FAP at the FC is rewritten by

$$P_f^{(\mathcal{FC}_1)} = 1 - \left[\left(1 - P_f^{(\mathcal{CR}_1)}\right)(1 - P_b(E_{C_1F})) + P_f^{(\mathcal{CR}_j)} P_b(E_{C_1F})\right]^{N_1}, \tag{36}$$

and lower-bounded by

$$P_{f,0}^{(\mathcal{FC}_1)} = \lim_{P_f^{(\mathcal{CR}_1)} \to 0} P_f^{(\mathcal{FC}_1)} = 1 - (1 - P_b(E_{C_1F}))^{N_1} \approx N_1 P_b(E_{C_1F}). \tag{37}$$

Thus, from (35), $P_{f,0}^{\prime(\mathcal{CR}_{1,j})}$ can be computed by

$$P_{f,0}^{\prime(\mathcal{CR}_{1,j})} = 1 - \left(1 - P_{f,0}^{(\mathcal{FC}_1)}\right)\left(1 - P_b(E_{FC_{1,j}})\right)^2 - P_b(E_{FC_{1,j}})(1 - P_b(E_{FC_{1,j}}))P_{f,0}^{(\mathcal{FC}_1)}. \tag{38}$$

Substituting (37) into (38), we obtain (24).

References

[1] Sendonaris, A., Erkip, E., and Aazhang, B.: ‘User cooperation diversity - Part I. System description’, IEEE Trans. Commun., Nov. 2003, 51, (11), pp. 1927–1938.

[2] Laneman, J., Tse, D., and Wornell, G.: ‘Cooperative diversity in wireless networks: Efficient protocols and outage behavior’, IEEE Trans. Inf. Theory, Dec. 2004, 50, (12), pp. 3062–3080.

[3] Mitola, I.J., and Maguire, J.G.Q.: ‘Cognitive radio: Making software radios more personal’, IEEE Pers. Commun., Aug. 1999, 6, (4), pp. 13–18.

[4] Wang, J., Ghosh, M., and Challapali, K.: ‘Emerging cognitive radio applications: A survey’, IEEE Commun. Mag., Mar. 2011, 49, (3), pp. 74–81.

[5] Yucek, T., and Arslan, H.: ‘A survey of spectrum sensing algorithms for cognitive radio applications’, IEEE Commun. Surveys and Tutorials, 2009, 11, (1), pp. 116–130.

[6] Cabric, D., Mishra, S., and Brodersen, R.: ‘Implementation issues in spectrum sensing for cognitive radios’, Proc. ACSSC’04, CA, USA, Nov. 2004, pp. 772–776.

[7] Zhang, W., and Letaief, K.: ‘Cooperative spectrum sensing with transmit and relay diversity in cognitive radio networks’, IEEE Trans. Wireless Commun., Dec. 2008, 7, (12), pp. 4761–4766.

[8] Ganesan, G., and Li, Y.: ‘Cooperative spectrum sensing in cognitive radio, part I: Two user networks’, IEEE Trans. Wireless Commun., Jun. 2007, 6, (6), pp. 2204–2213.

[9] Mishra, S., Sahai, A., and Brodersen, R.: ‘Cooperative sensing among cognitive radios’, Proc. IEEE ICC’06, Istanbul, Turkey, Jun. 2006, pp. 1658–1663.

[10] Letaief, K., and Zhang, W.: ‘Cooperative communications for cognitive radio networks’, Proc. of the IEEE, May 2009, 97, (5), pp. 878–893.

[11] Simeone, O., Bar-Ness, Y., and Spagnolini, U.: ‘Stable throughput of cognitive radios with and without relaying capability’, IEEE Trans. Commun., Dec. 2007, 55, (12), pp. 2351–2360.

[12] Han, Y., Pandharipande, A., and Ting, S.: ‘Cooperative decode-and-forward relaying for secondary spectrum access’, IEEE Trans. Wireless Commun., Oct. 2009, 8, (10), pp. 4945–4950.

[13] Zou, Y., Zhu, J., Zheng, B., and Yao, Y.-D.: 'An adaptive cooperation diversity scheme with best-relay selection in cognitive radio networks', IEEE Trans. Signal Process., Oct. 2010, 58, (10), pp. 5438–5445.

[14] Digham, F.F., Alouini, M.-S., and Simon, M.K.: 'On the energy detection of unknown signals over fading channels', IEEE Trans. Commun., Jan. 2007, 55, (1), pp. 21–24.

[15] Gradshteyn, I.S., and Ryzhik, I.M.: 'Table of Integrals, Series, and Products', Academic Press, 7th edn. 2007.

[16] Simon, M.K., and Alouini, M.-S.: 'Digital Communication over Fading Channels', John Wiley & Sons, 2nd edn. 2005.